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RESEARCH MEMORANDUM

PRELIMINARY ANALYSIS OF PERFORMANCE OF TURBOJET ENGINES USED AS PUMPS FOR BOUNDARY-LAYER CONTROL

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The effects on engine performance of using turbojet engines for boundary-layer control by suction at the engine inlet or by bleeding air from the compressor outlet were determined for three current production engihes. In addition, the quantities of bleed and suction flow available are given. Except for the effect of intercompressor bleed on one engine, obtained experimentally, all results are based on calculations using experimentally determined component performance maps.

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Compressor-outlet bleed flows of between 32 and 43 percent could be obtained before the engine net thrust was reduced to zero; however, the specific fuel consumption increased at an extreme rate for bleed flows above 20 percent. With suction, the maximum possible flow is, of course, the total engine air flow. Both the maximum flow and the net thrust decreased linearly with the reduction in pressure at the engine inlet. Specific fuel consumption rose at an increasing rate as the engine-inlet pressure was reduced.

A brief examination was made to determine whether or not the use of a variable-area turbine would be beneficial. No effect on performance was obtained other than higher pressures were available for the bleed flow.

INTRODUCTION

A strong interest is currently in evidence regarding the use of boundary-layer control to improve the cruise, landing, and take-off performance of aircraft through improved lift-drag ratios. Theoretical studies such as that of reference 1 have shown the possibility for very large increases in aircraft range with complete removal of the boundary layer on all aircraft surfaces. Boundary layer supercharging with air bled from the compressor has already been demonstrated to improve the low-speed performance of an F9F-4 airplane (ref. 2). Both suction and supercharging of the boundary layer are under consideration in design studies of future aircraft. The use of currently available conventional turbojet engines as a source of pumping is an obvious possibility, and it is necessary that the suitability of these engines for such purposes be determined before the studies can become "concrete" efforts. Accordingly, a brief preliminary study was made to determine the suitability of three modern turbojet engines for which adequate component performance data were available.

The engines studied are designated by the letters A, B, and C. The optimum mode of engine operation with bleed was first determined, and the effect of compressor-outlet bleed on the performance of the first two engines was calculated. The performance shown for a two-spool engine (C) with intercompressor bleed flows up to 10 percent of engine flow was based on experimental data. The performance of all three engines when used for suction was computed for a range of engine-inlet total pressures, selected to cover the expected range of slot and duct pressure losses. In addition, the merits of using a variable-area turbine were determined.

The analytical procedure for bleed calculations consisted simply of simultaneous solution to satisfy conditions of flow continuity at the turbine and exhaust nozzle and the condition which requires that the turbine work equal the compressor work. When a fixed-area exhaust nozzle was used, the simultaneous solution was obtained by a method of iteration. For suction, the engine performance was calculated from the experimentally determined pumping characteristics for the respective engines. The use of pumping characteristics to calculate the effect of inlet duct (suction case) losses on engine performance is discussed in reference 3.

RESULTS AND DISCUSSION

Inasmuch as the analytical procedure (although lengthy) was quite simple, and is not of primary interest, it is not given in detail. Only that portion of the analysis involving the use of a fixed-area exhaust nozzle (mode-2 operation to be described) was not straightforward. For the calculations involving the fixed-area exhaust nozzle, the procedure outlined in the appendix was used.

In the following sections, several modes of engine operation for bleedoff are discussed first. Using the mode selected as optimum, the engine performance with bleed is then given for operation at take-off, landing, and cruise conditions. The calculations were carried out with bleed flows increasing to a point where zero thrust was reached. Engine performance at thrust levels near zero is of interest, because it is anticipated that on a multiengine airplane some of the engines would be used for boundary-layer-control purposes while others would be used only for thrust.

Next, the characteristics of the engines when used to provide boundary-layer suction are presented for operation at take-off, landing, and cruise operation. Finally, the possible advantages of using a variable-area turbine in conjunction with bleed are discussed.

Bleed

Mode of engine operation. - The path of the compressor operating point for two possible modes of engine operation during take-off is superimposed on the conventional compressor map of engine A in figure 1. These modes are described as follows:

(1) Mode 1 (variable-area exhaust nozzle) - The path of the compressor operating point starts at the military operating condition (point A) where bleedoff from the compressor discharge is begun and the exhaust-nozzle area is simultaneously opened to maintain limiting turbine-inlet temperature and rated engine speed. At point B, limiting loading of the turbine was reached at a bleed flow β of 23 percent. Throughout this report, the bleed flow is defined as the ratio of bleed flow to engine-inlet air flow at rated engine speed.

From point A to B, it was possible to increase the turbine work per pound of gas by opening the exhaust nozzle to reduce the back pressure on the turbine. Hence, engine speed could be maintained as the turbine gas flow decreased with increasing bleedoff at the compressor outlet. At point B, however, the flow at the turbine rotor outlet reached sonic velocity (a condition called limiting loading); consequently, no increase in turbine work was possible by further reduction in back pressure.

By reducing engine speed and hence compressor pressure ratio, it was possible to increase the bleed flow to 33 percent at point C where the net thrust was reduced to zero. From B to C, limiting loading of the turbine and limiting turbine-inlet temperature were maintained by further opening of the exhaust nozzle.

(2) Mode 2 (rated exhaust-nozzle area) - The path of the compressor operating point again started at the military condition (point A) where the engine speed was reduced and the bleed flow simultaneously increased to hold limiting turbine-inlet temperature. Because the method of iteration used was laborious, this calculation was terminated at point D where the thrust was 50 percent and the bleed flow was 19.3 percent. This range, however, was adequate for comparison of the two modes.

Performance for the two modes of operation are compared in figure 2 where the net thrust per unit engine weight and the specific fuel consumption with bleed divided by the specific fuel consumption with no bleed are shown as functions of the bleed flow. It is seen that there is very little difference in performance for the two modes.

For operation at a thrust level intermediate between take-off and landing thrust, two additional modes of operation are considered. These modes are defined as follows:

(3) Mode 3 - Both engine speed and exhaust-nozzle area were held constant, and the turbine-outlet temperature was allowed to increase with increasing bleed.

(4) Mode 4 - Operation at constant thrust lower than military is possible over a limited range of bleed flows by holding rated exhaust-nozzle area and increasing engine speed as bleed flow increases. The turbine-inlet temperature will increase with bleed for this mode.

The four modes of operation are compared in figure 3. These data were obtained by use of the matching charts of reference 4 for another engine. Net thrust is shown in ratio form, with the net thrust with bleed at a flight Mach number of 0.62 being divided by the military thrust at static conditions. This particular ratio was used only as a matter of convenience in applying the charts of reference 4 and in no way detracts from the validity of the comparison of the operating modes.

For this engine, also, there is no appreciable difference in thrust for modes 1 and 2. For mode-3 operation, the thrust was somewhat higher for a given bleed flow; however, the turbine-inlet temperature also increased with bleed as shown in the lower portion of figure 3. Because cruise operation for long periods of time is undesirable at turbine temperatures higher than normally used for cruise, mode-3 operation was not considered further. For mode-4 operation (constant thrust), the turbine-inlet temperature increased even more rapidly, and accordingly mode 4 was given no further consideration.

For both engine A and the engine of reference 4, it is seen from figures 2 and 3 that there is no clear choice between modes 1 and 2 on the basis of performance. This is corroborated by experimental data for another engine in reference 5. Mode-1 operation, however, has the advantage that the engine speed is higher for any given thrust level, and hence military power may be more quickly restored than for mode 2. Accordingly, mode-1 operation is used for all subsequent bleed results on engines A and B. The experimental data to be presented for engine C were obtained only for mode-2 (fixed-nozzle) operation.

Take-off performance with bleed. - In order to include the critical point during take-off at which obstacles must be cleared, the take-off condition was chosen as a Mach number of 0.15 (99 knots) at NACA standard sea-level conditions. The bleed pressure available, net thrust, and specific fuel consumption are shown in ratio form as functions of percent bleed in figure 4. Limiting loading of the turbine existed for all bleed flows to the right of the cross marks superimposed on the curves. Because of its higher compressor pressure ratio, engine A gave higher bleed pressures than did engine B. The intercompressor bleed from engine C was, of course, at much lower pressure.

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Net thrust per unit weight fell off linearly with bleed for engines A and B until limiting loading occurred. The slope for engine A was about 2.2 percent thrust loss for 1 percent bleed. For engine B it was about 1.9 percent thrust loss per percent of bleed. Beyond the point of limiting loading, the thrust decreased more rapidly, with engine A reaching zero thrust at about 33 percent bleed and engine B reaching zero thrust at about 43 percent bleed. Thrust of engine C, with mode-2 operation, fell off at a rate of 2.8 percent per percent bleed.

The specific fuel consumption for all three engines increased at about the same rate up to 10 percent bleed. The curves for engines A and B diverged beyond that point. This separation is attributed to slight differences in component efficiency which became amplified as the net thrust approached zero. For both engines, the specific fuel consumption began to increase at a much more rapid rate somewhat before limiting loading was reached, or at bleed flows roughly on the order of 20 percent. It should be noted, however, that although the specific fuel consumption increased with bleed, the actual fuel consumption decreased.

Landing performance with bleed. - Data for the landing condition are presented in figure 5. Specific fuel consumption was dismissed as being unimportant at landing and is therefore not presented. In accordance with the Navy practice of maintaining 40 percent thrust until the throttle "chop," the base condition with no bleed was taken as 40 percent of military thrust. With engines A and B, the exhaust nozzle was in an open position to permit the highest possible engine speed for the base point (no bleed). Limiting turbine loading existed for this base condition. With engine speed held constant at the initial value, the nozzle was opened further as needed for all subsequent bleed points to hold limiting loading as bleed flow increased. In order to obtain 40 percent thrust with a fixed-area exhaust nozzle, the engine speed must be lower than for a variable-area nozzle; hence, the percent engine speed was slightly lower for engine C than for the other engines. Zero thrust occurred at 32 percent bleed for engine A and at 34 percent bleed for engine B.

Cruise performance with bleed. - The cruise condition was selected as a flight Mach number of 0.9 at an altitude of 40,000 feet. The base (no-bleed) condition was selected as 90 percent of military thrust. For engines A and B, the engine mechanical speed was picked at 95 percent with the required temperature level being obtained with the variable-area exhaust nozzle. For all succeeding bleed conditions, the turbine-inlet temperature was then held at this value by either an area adjustment at constant speed (to limiting loading) or a speed reduction (beyond the initial limiting-loading point). For engine C, the base mechanical speed (no bleed) was selected at 97 percent and was then reduced as bleed increased to hold the turbine-inlet temperature at the base value.

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The data for the cruise performance presented in figure 6 show trends very similar to those obtained at take-off (fig. 4). Zero thrust occurred at a bleed flow of 33 percent for engine A and 42 percent for engine B. One difference from take-off was apparent, however, in that engine C, which had the lowest thrust per unit weight at take-off, had the highest thrust per unit weight at the cruise condition. This shift in relative position is characteristic of engine C and is due in part to an increase in the actual speed of the outer spool for a fixed inner-spool speed, which is held constant by the engine control. In addition, the maximum permissible turbine-inlet temperature of engine C is allowed to increase with altitude. For cruise, just as for take-off, the specific fuel consumption began to increase at an extreme rate at bleed flows on the order of 20 percent.

Thus, from the data of figures 4 to 6, it is seen that bleed flows as high as 32 to 43 percent were possible for the various engines and flight conditions; however, the specific fuel consumption rose at an extreme rate for bleed flows greater than about 20 percent.

Suction

In order to provide boundary-layer suction, it is necessary that the pressure at the exit of the suction duct be maintained at a sufficiently low level that the desired quantity of suction flow is induced. If the suction air discharges into the main air inlet duct at the engine inlet, it is necessary that a throttle valve be used near the main duct inlet to reduce the pressure of all the engine air to a value needed to induce the desired suction flow. If it is assumed that flow distortions are not produced by the throttle valve or suction-duct discharge jets, the engine will "be aware" only of the pressure at the face of the engine. Thus for a given pressure at the face of the engine, the engine performance will be the same irrespective of the relative amounts of air arriving via the suction duct and through the throttle valve. The maximum suction flow available for boundary-layer removal is, of course, the total engine air flow and is a direct function of the pressure at the engine inlet.

It is conceivable that local pockets of low pressure could be created at the discharge of the suction duct by the use of devices (similar to cowl flaps) which cause local acceleration of the main air-flow column entering the engine. Although such devices would probably produce
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Take-off with suction. - The effects of suction flow on engine performance at take-off are given in figure 7. Inasmuch as the exhaust nozzle was choked for all conditions covered at the take-off condition, the turbine-inlet temperature was not altered as the engine-inlet pressure decreased. Net thrust, maximum suction flow, and specific fuel consumption are given in ratio form as functions of the ratio of engine-inlet total pressure to free-stream total pressure. Because the pressure losses in the suction duct will vary among installations, the range of pressures assumed at the engine inlet was selected to cover a wide range of duct pressure losses. For all three engines, it is seen that the net thrust and maximum suction flow decrease linearly with engine-inlet pressure (or inversely with duct loss). The specific fuel consumption based on net thrust, however, does not increase linearly but rises at an increasing rate as the engine-inlet pressure is reduced. The trend is explained by the fact that the net thrust is reduced by both a decrease in exhaust-nozzle pressure ratio and a reduction in air flow, whereas the fuel flow decreases in proportion to the air flow only.

Landing performance with suction. - The relative performance of the three engines at the landing condition of 99 knots (40 percent of military thrust for zero pressure drop) is shown in figure 8. Again the net thrust and maximum suction flow decreased linearly with engine-inlet total pressure. The maximum suction flow with engine C is less than for the other engines because of the more rapid decrease in air flow for that engine as the speed was reduced to the 40-percent-thrust base condition.

Cruise performance with suction. - The results on cruise performance with suction are shown in figure 9. The cruise conditions were the same as those defined earlier in conjunction with figure 6. Again the net thrust and maximum suction flow decrease linearly with engine-inlet total pressure. Just as at the take-off condition, the specific fuel consumption increases more rapidly at the lower values of engine-inlet total pressure. The specific fuel consumption was somewhat higher for engine A at low values of engine-inlet total pressure because small differences in component efficiency have a more pronounced effect as the engine net thrust goes toward zero. 3771

Variable-Area Turbine

Inasmuch as a variable-area turbine affords an independent method of controlling turbine-inlet temperature, its use in conjunction with compressor bleed is of interest. The effect of using a variable-area turbine in conjunction with bleed was calculated for engine B at take-off, assuming the following effect of turbine area on turbine efficiency:

Turbine-area decrease, percent	Turbine efficiency loss, percent
10	0.5
20	2.5
30	6.0

From figure 10 it is seen that the variable-area turbine affords no appreciable advantage in performance other than an increase in the bleed pressure available at any given value of bleed flow.

CONCLUDING REMARKS

From this brief preliminary analysis for three current production engines, it was found that compressor bleed flows as high as 32 and 43 percent could be obtained before the engine net thrust was reduced to zero. The specific fuel consumption increased at an excessive rate for bleed flows greater than about 20 percent; however, the actual fuel flow was reduced. With the engine used for suction, the maximum possible flow is, of course, the engine air flow. Both the maximum suction flow and the net thrust decreased linearly with the reduction in engine-inlet total pressure (increased suction-duct losses). Specific fuel consumption based on net thrust rose at an increasing rate as the engine-inlet pressure was reduced.

The possible advantage of using a variable-area turbine was examined in conjunction with compressor bleed. It was found that this device offered no advantage other than the availability of higher bleed pressures at a given percentage of bleed flow.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 23, 1955

APPENDIX - CALCULATION PROCEDURE

The method of iteration used in determining the engine performance with bleed for operation with a fixed-area exhaust nozzle is not given in detail; however, the procedure is outlined in the following paragraphs.

In the consideration of the take-off condition, it was desired to determine the engine performance as the speed was reduced and the compressor-outlet bleed flow increased at such a rate that the limiting turbine-inlet temperature would be maintained. At some arbitrary engine speed below military, a bleed flow was assumed to exist. With the knowledge (obtained after the first trial) that the compressor pressure ratio would decrease, the air flow through the compressor and hence through the turbine (subtracting the assumed bleed flow) was determined. By using the continuity equation for choked flow through the turbine diaphragm, and an effective turbine flow area determined from experimental data, the total pressure at the turbine inlet was found for operation at the limiting temperature value. With this value and an assumed combustor pressure loss of 5 percent, the compressor pressure ratio was obtained. From this and the compressor efficiency obtained from the compressor performance map, the compressor work was calculated. Equating the compressor work to the turbine work allowed a solution for the turbine-outlet temperature, and, by knowing the mass flow, the turbine-outlet pressure was obtained from the exhaust-nozzle flow equations (either choked or unchoked as required). By using a value of turbine efficiency from the turbine performance map, the turbine-inlet pressure was again computed. This value was then compared with the trial value obtained earlier in the calculation, and new values of bleed flow were assumed for repeated calculations until the two values of turbine-inlet pressure agreed. When agreement was obtained, the requirements of flow continuity and work balance between the compressor and turbine were satisfied.

Although this method of iteration was laborious, it was only necessary for a few operating points. Had this mode of engine operation (with a fixed-area nozzle) been optimum, the work required to construct matching charts, such as those given in reference 4, would have been warranted for the much larger number of operating conditions requiring solution.

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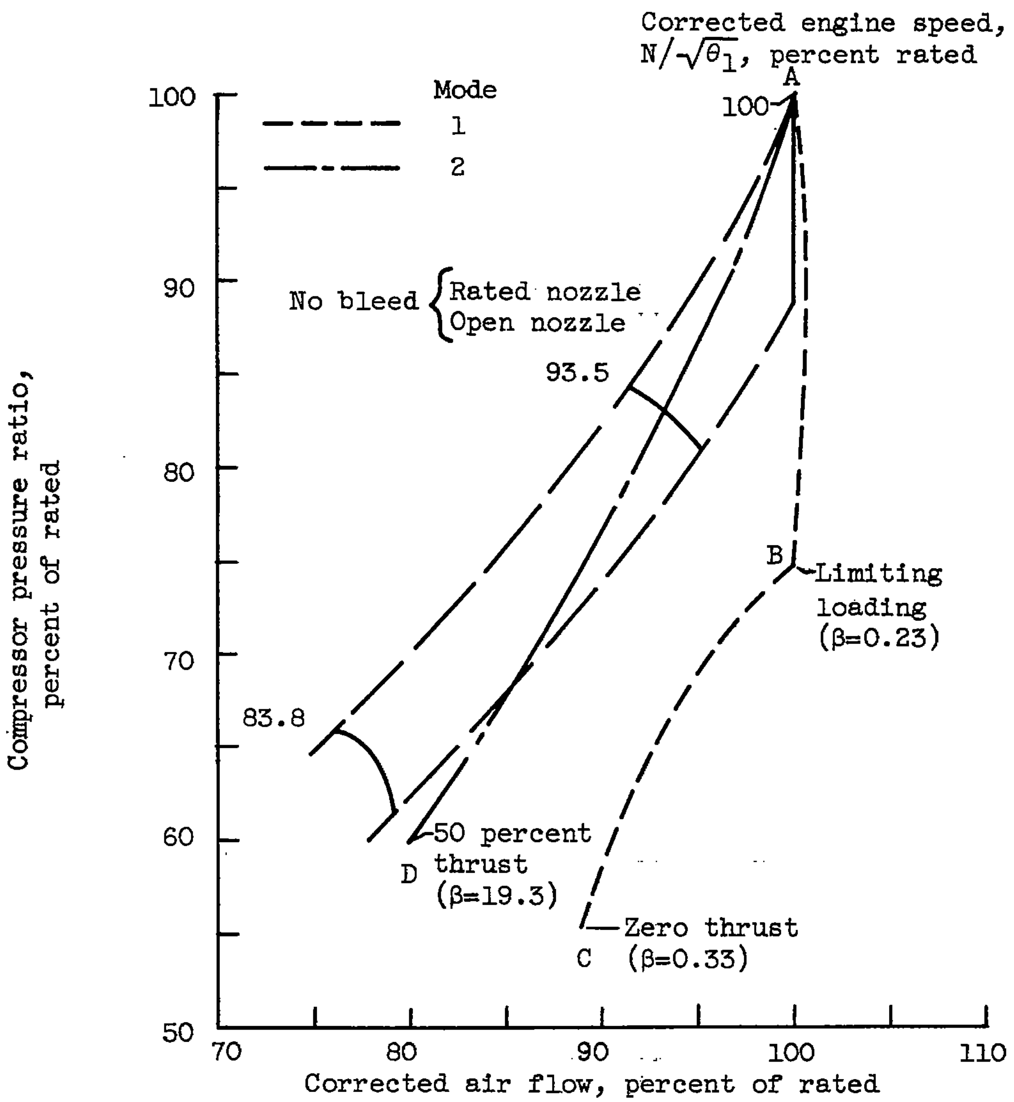

Figure 1. - Two possible modes of engine operation for take-off with bleed for engine A.

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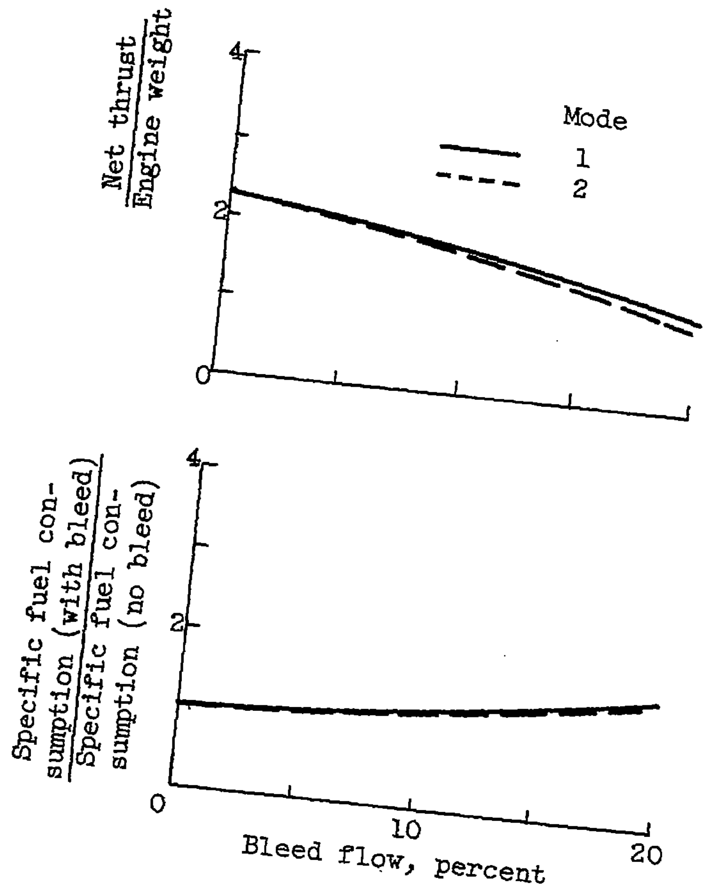

Figure 2. - Effect of engine operating modes on performance of engine A at take-off. Altitude, sea level; flight Mach number, 0.15.

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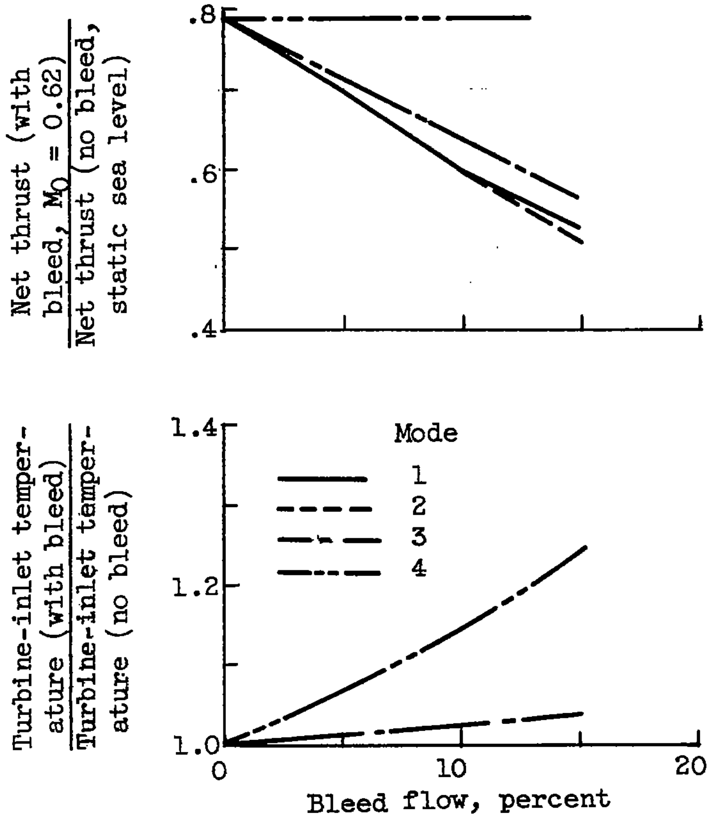

Figure 3. - Effect of engine operating modes on performance of engine D. Altitude, sea level; flight Mach number, 0.62.

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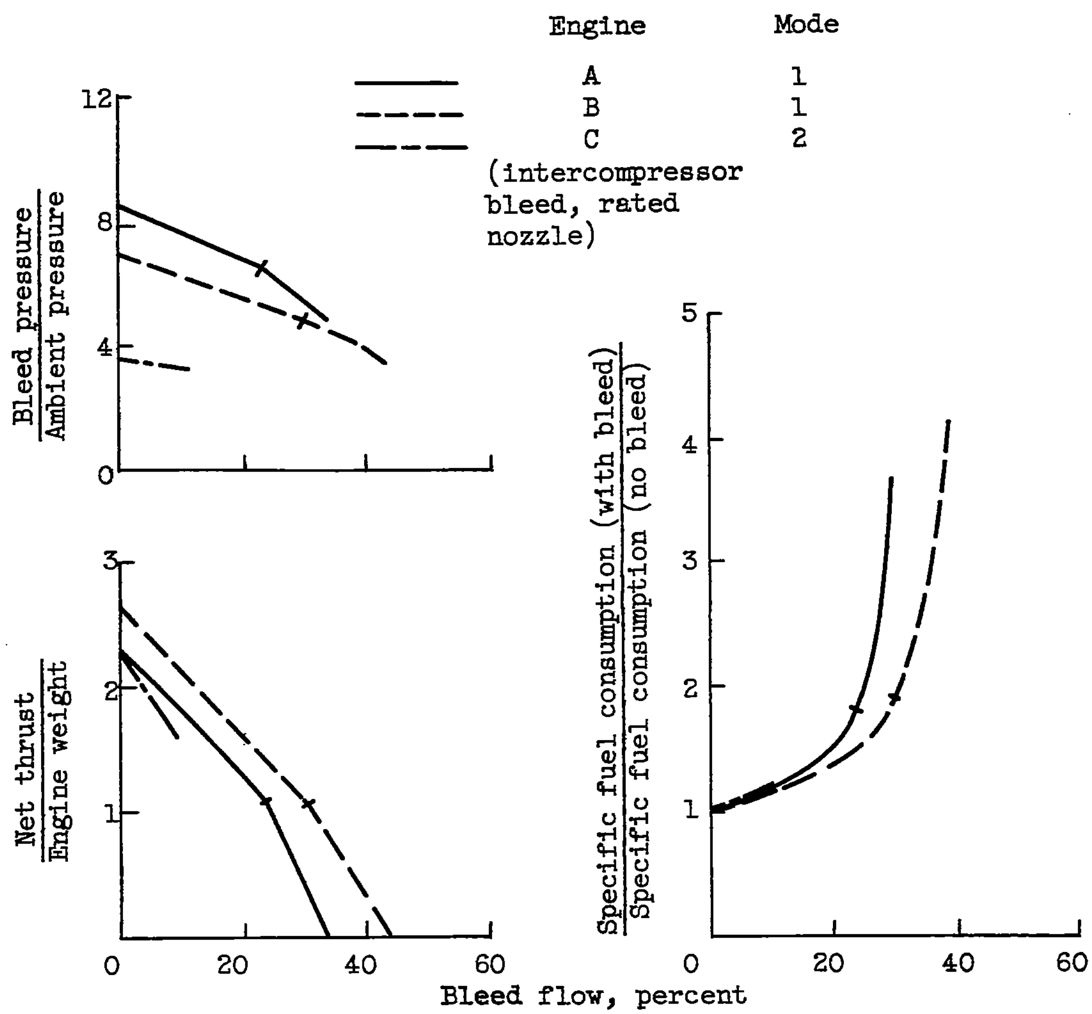

Figure 4. - Take-off performance with bleed.

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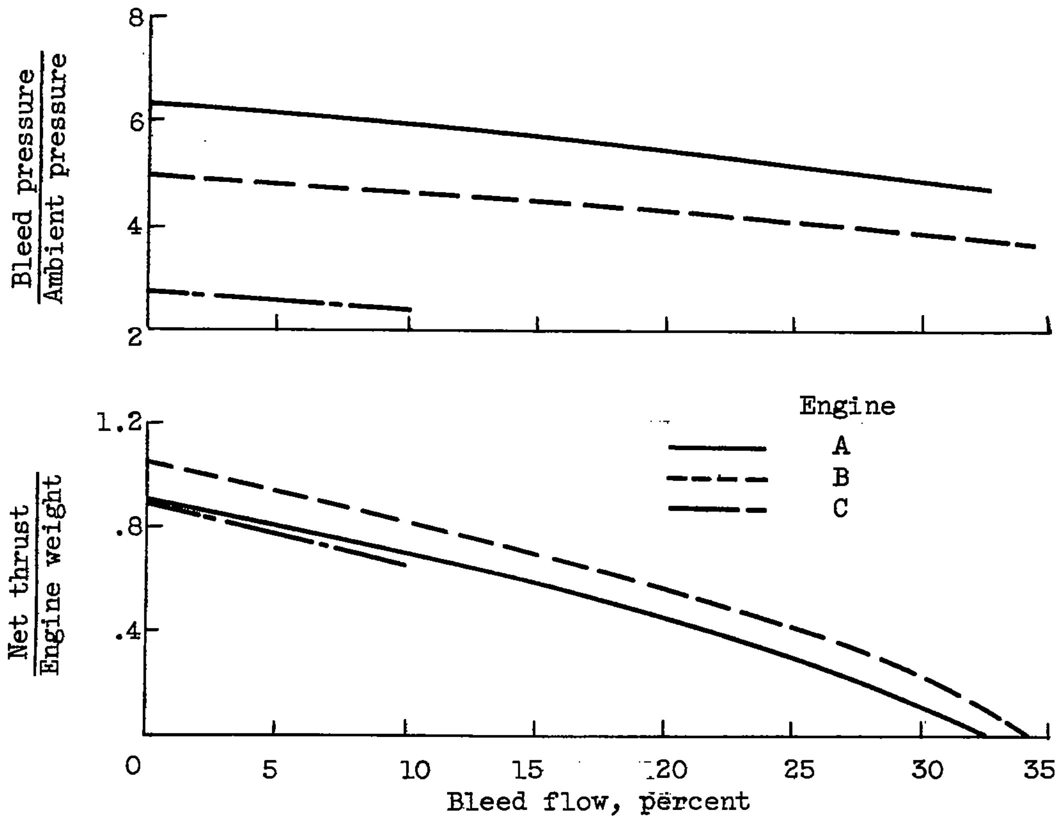

Figure 5. - Landing performance with bleed.

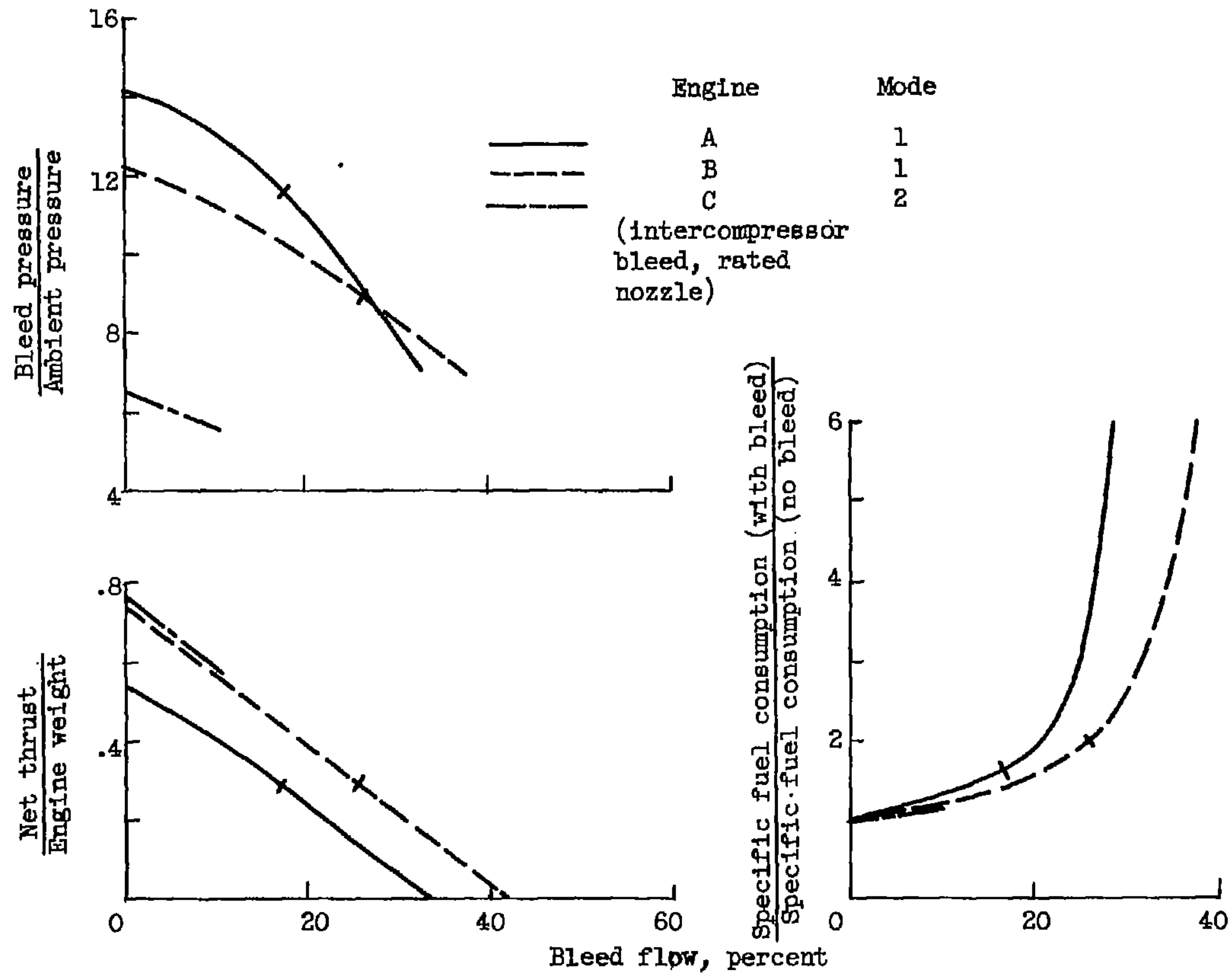

Figure 6. - Cruise performance with bleed. Altitude, 40,000 feet; flight Mach number, 0.9.

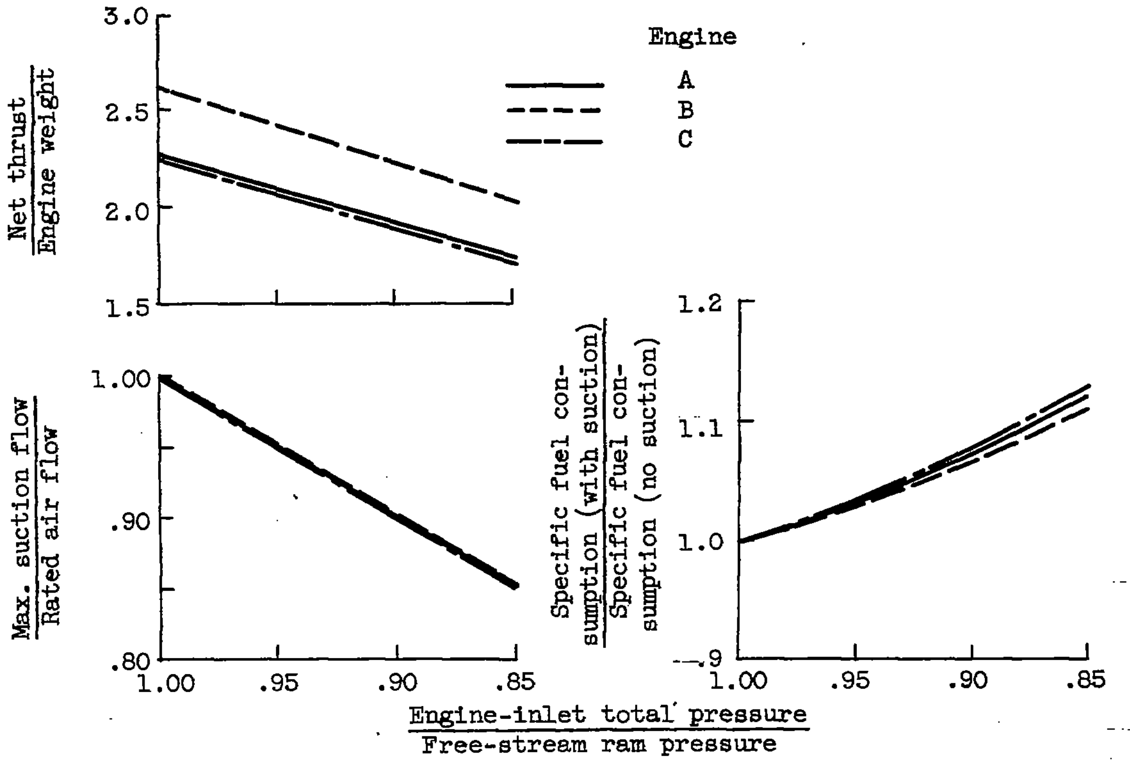

Figure 7. - Take-off performance with suction. Rated engine speed, rated temperature.

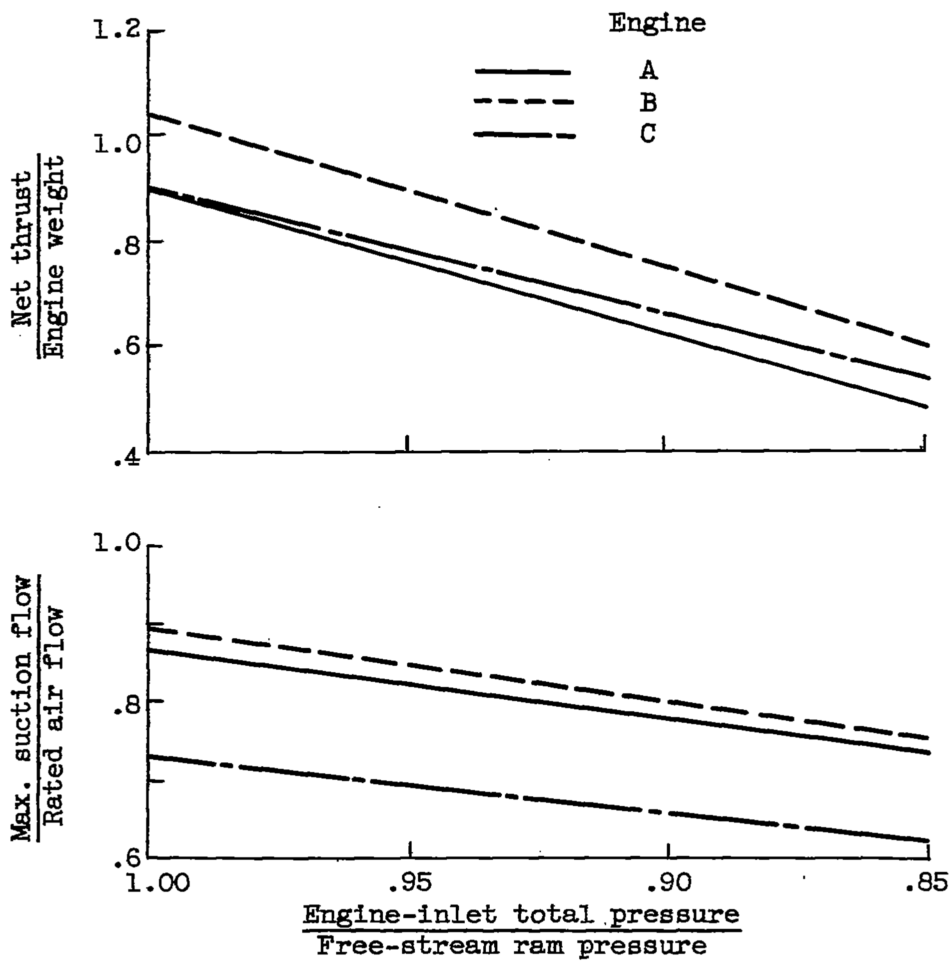

Figure 8. - Landing performance with suction.

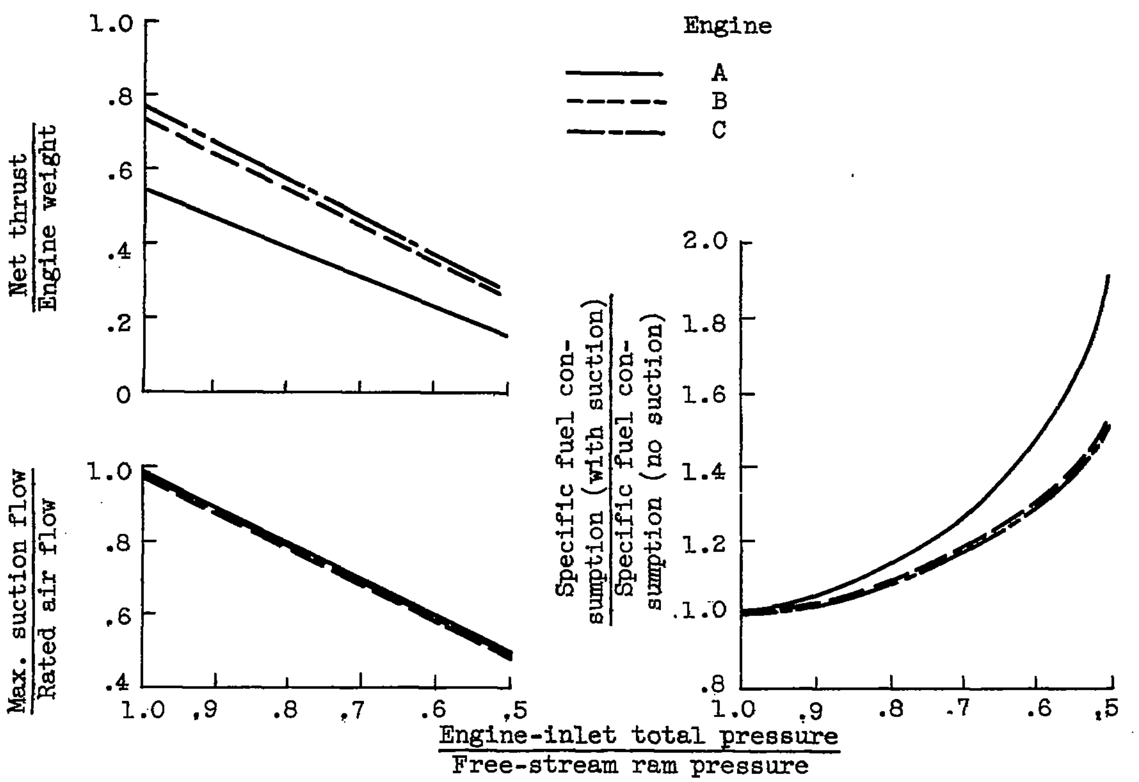

Figure 9. - Cruise performance with suction. Altitude, 40,000 feet; flight Mach number, 0.9.

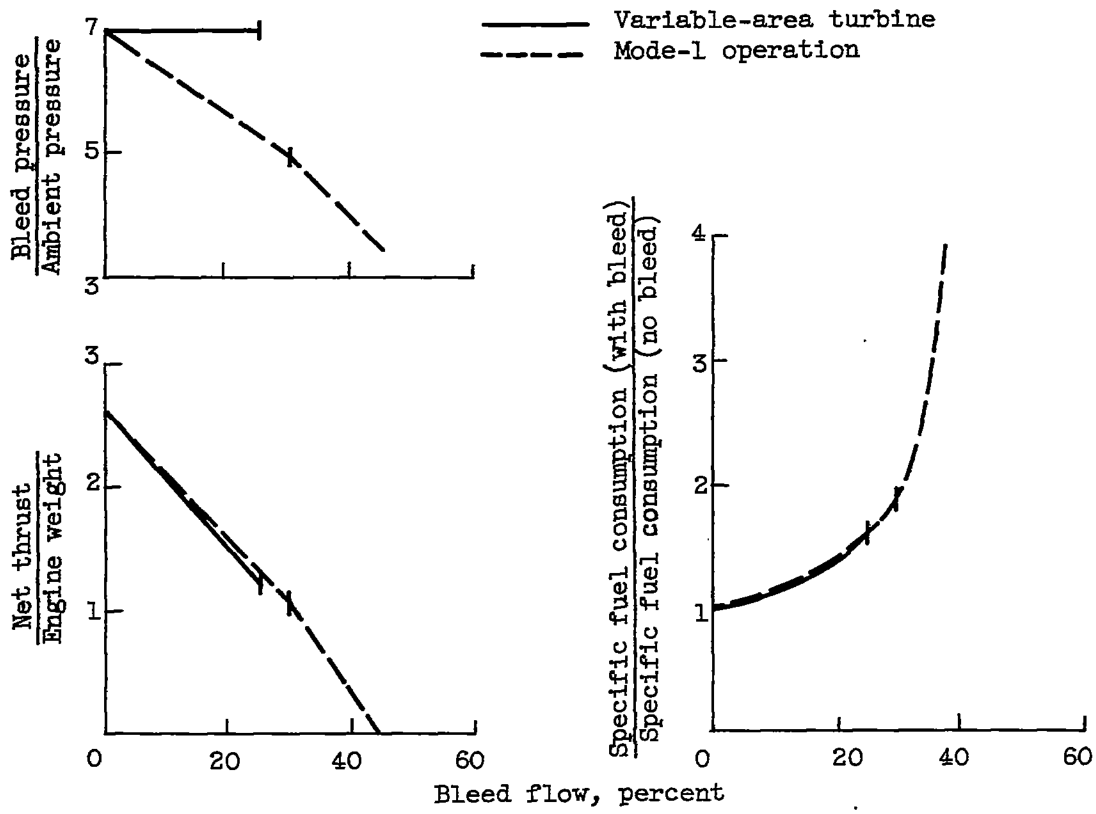

Figure 10. - Effect of variable-area turbine. Engine B; take-off conditions.

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